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An aerial diversity switch for the Channel Islands television re-broadcast link

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Summary

The report describes an experimental diversity switch which operates during the field blanking period of the television waveform. The switch is solid state and operates very rapidly to minimize the disturbance to the television waveform. The results of an experimental period of operation are given.

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Research Department, Engineering Division,
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1. Introduction

Fading on long-distance re-broadcast links can cause serious impairment of the re-transmitted signal. During fades the signal-to-noise ratio of the signal will be degraded and any co-channel interference present will become more apparent. To combat such effects diversity reception may be used. The principle is to obtain two or more signals which have traversed different paths or have otherwise been subject to different propagation influences, so that there is little correlation between variations in level. The signals are then combined or selected so as to give a resultant having less deep fades than any one component. Various means may be employed to obtain uncorrelated signals. That most commonly used, and of most interest in the present context, is the use of spaced aerials. Frequency diversity and polarisation diversity are other methods though the latter may not be very effective at ultra-high frequency (u.h.f.). Angle diversity is used on scatter propagation links and involves large aperture aerials fitted with dual feeds.

The work described in this report was undertaken in connection with the u.h.f. television re-broadcast link to the Channel Islands. The signal is radiated from Stockland Hill in Devon and received on the island of Alderney, a path distance over sea of 145 km. There are several aerials on the receiving site and it is expected that two of these will provide adequate diversity. From Alderney the signal is sent on to the transmitter at Fremont Point, Jersey, by means of a super-high-frequency (s.h.f.) link.

The diversity switch to be described was built to investigate some of the parameters that affect the performance of a diversity system and to find out what order of improvement could be obtained at the Alderney receiving site by using two-channel diversity. It differs from earlier switches in employing a fast-acting solid-state switch synchronized to the television waveform.

2. Signal statistics

2.1. The received signal

The propagation path from Stockland Hill to Alderney extends beyond the radio horizon so that the signal is propagated by diffraction, by tropospheric scattering and by reflection at the boundaries between different air masses. The statistics of the variation of the signal have been measured[1] and are given in Fig. 1. Of particular interest is the shape of the distribution curve for low signal strengths. This is not very well defined, partly because a sophisticated recording technique is needed to deal with a rapidly fading signal and partly because a long period of measurements is essential.

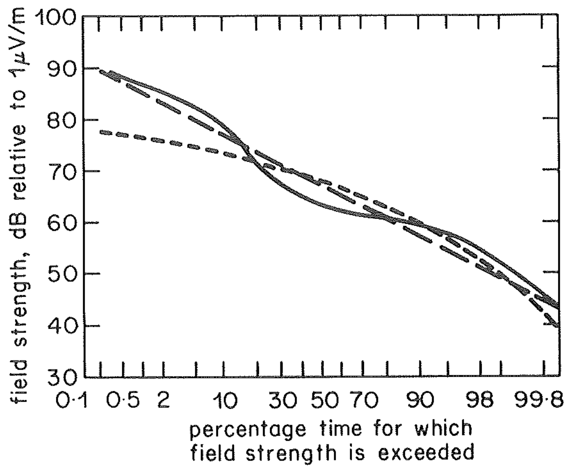

Fig. 1 - Probability distribution of Stockland Hill signals on Alderney

measured distribution
logarithmic Gaussian distribution
Rayleigh distribution

In addition to the measured distribution of the received signal Fig. 1 also shows a logarithmic Gaussian distribution that gives a reasonable overall fit and a Rayleigh distribution that follows the measured shape more closely at lower levels. This is understandable as, when the signal level is low, the fading pattern tends to exhibit the characteristics of a scattered signal for which the Rayleigh distribution is theoretically appropriate.

2.2. Gaussian distribution

The probability that a signal with a Gaussian distribution lies between levels x and $x + dx$ is given by

$$p_x(x)\,dx = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{\frac{-x^2}{2\sigma^2}\right\} dx \qquad \ldots\ldots (1)$$

where x is the deviation of the signal amplitude from its mean value and σ is the standard deviation. If the signal amplitude is expressed in decibels we have the logarithmic Gaussian or log-normal distribution.

The integral of this expression gives the probability that the signal is less than some level s, measured from the mean level, and may be shown to be[2]

$$P(s) = \tfrac{1}{2}\,(1 + \mathrm{erf}\ {}^{s}/2) \qquad \ldots\ldots (2)$$

$$\text{where } \operatorname{erf} s/2 = \frac{2}{\sqrt{\pi}} \int_0^{s/2} e^{-t^2}\, dt$$

When there are two such signals which are uncorrelated, the probability that both are less than some level s is[2]

$$P'(s) = [\tfrac{1}{2}(1 + \operatorname{erf} s/2)]^2 \qquad \ldots\ldots (3)$$

The probability distributions of Equations 2 and 3, with the amplitudes expressed in decibels, are shown in Fig. 2. The difference between them for a given percentage of time is termed the diversity gain.

2.3. Rayleigh distribution

The probability that a signal voltage lies between levels x and $x + dx$ is given by

$$p(x)dx = \frac{2x}{\sigma^2} \exp\left\{\frac{-x^2}{\sigma^2}\right\} dx \qquad \ldots\ldots (4)$$

where σ is the r.m.s. value of the signal measured from zero. Here x is the signal amplitude (in linear measure) and so is restricted to positive values.

The mean value is given by

$$\bar{x} = \tfrac{1}{2}\sigma\sqrt{\pi} \qquad \ldots\ldots (5)$$

The probability integral is given by[3]

$$P(s) = \int_0^s p(x)\, dx$$

$$= 1 - e^{-s^2/\sigma^2} \qquad \ldots\ldots (6)$$

For a dual-diversity system

$$P'(s) = \left[1 - e^{-s^2/\sigma^2}\right]^2 \qquad \ldots\ldots (7)$$

The probability distributions of Equations 6 and 7 are shown in Fig. 3. The diversity gain is greater in this case but it should be remembered that the depth of fading is greater to begin with.

2.4. Unequal signals

Hitherto it has been assumed that the median values of the two signals are the same. In practice this is often not the case. Different aerials may have different gains, be illuminated by different field strengths or have different feeder loss to the point where the comparison is made. It

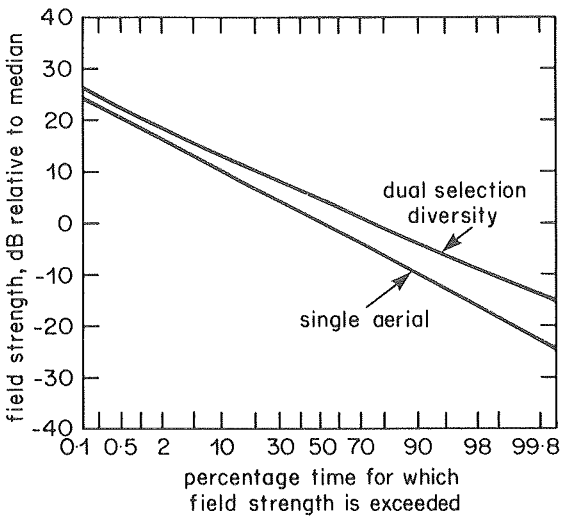

Fig. 2 - Dual selection diversity with logarithmic Gaussian fading

may be shown[2] that, in such cases, the calculated diversity gain is achieved relative to a single receiver which delivers a signal at a level equal to the arithmetic mean of the levels of the actual constituent signals, when expressed in decibels.

3. Selection diversity

In the previous section it was assumed that the means existed for selecting the strongest of the individual signals at any instant of time. This process, called selection diversity, must be considered in more detail. Other methods may, however, be mentioned at this stage.[3] In

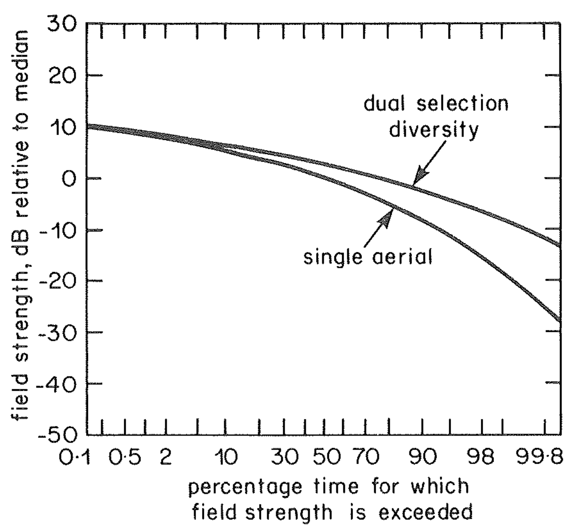

Fig. 3 - Dual selection diversity with Rayleigh fading

equal-gain diversity the signal channels have the same gain and the demodulated signals are simply added together. In **maximal-ratio diversity** the gains of the signal channels are adjusted to give signals weighted according to the signal/noise ratio.[4] Both these methods give slightly better signal-to-noise ratios but are difficult to implement with television signals. Accordingly consideration was restricted to selection diversity.

In order to realize the full diversity gain, the switch must be able to operate on small differences of signal level. At times this will result in very frequent operation. In the past, slow-acting mechanical switches have been used and each switching operation tended to disturb the transmitted television picture with splashes or loss of synchronization. To ameliorate this impairment the switch had to be designed to operate with backlash, i.e. the difference between the signals had to be quite large – sometimes as much as 10 dB – before the switch would operate. This reduced picture disturbances but nullified any diversity gain except for long slow fades.

To effect an improvement it is necessary to have a fast-acting switch which operates at a non-critical point in the video signal. Moreover, it is necessary to match the two channels and to equalize timing differences so that the switching action is invisible on the received picture. It is possible that propagation and other effects may limit the degree of equality between channels that can be maintained over long periods. It might then be necessary to introduce backlash again, but it should be remembered that this will at the same time detract from the diversity gain.

So far it has been assumed that the switch will operate on signal level. However, the purpose of a diversity receiving system is to maintain a high signal-to-noise ratio and the signal level at the input of the receivers is not necessarily a measure of this; it will depend also on the amount of pre-amplification that has been used. A more satisfactory method of controlling the switch is to measure the video signal-to-noise ratio from each receiver and then to switch to the best video signal. This will also minimize the visibility of switching in respect of picture noise.

It has also been assumed that the switch will operate at all levels. This is unnecessary when both signals are sufficiently high to give good signal-to-noise ratios. It is also undesirable since occasional very high signal strengths may cause non-linearity in the pre-amplifiers. The switch should therefore be designed so that no action is taken when both signals are above a fairly high threshold level.

4. The experimental diversity system

The experimental diversity system is a two-channel unit containing two independent receivers. A switch may select the outputs (both sound and vision) of either receiver. The switch can be operated on one of two criteria: to select either the receiver with the greater signal at its output or the receiver with the better video signal-to-noise ratio.

4.1. Selection on signal level

In this mode the automatic gain control (a.g.c.) voltages of the receivers are used to select the receiver with the greater signal level at its input (see Fig. 4). A threshold level is used; if either of the signals goes above this threshold then that signal will be selected and retained as long as it remains above threshold. If both signals are below threshold then the stronger signal is selected. Table 1 shows a truth table of the switching operation.

The threshold was set at about 1 mV at the inputs of the receivers; this corresponds to a video peak-to-peak to r.m.s. noise ratio of about 44 dB. Below threshold no backlash was added.

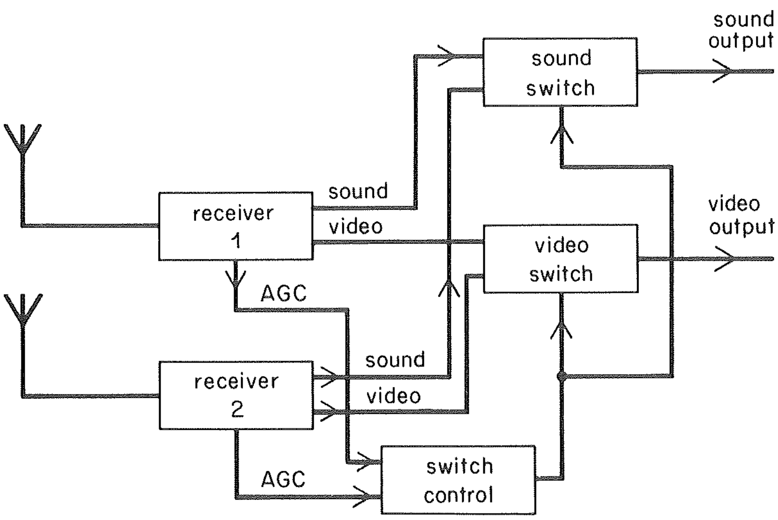

Fig. 4 - Selection on signal level

TABLE 1

Switch truth table

Channel 1	Channel 2	Selected
Above Threshold	Below Threshold	1
Above Threshold	Above Threshold	Whichever was above threshold first
Below Threshold	Below Threshold	Whichever is greater
Below Threshold	Above Threshold	2

The main problem of comparing the signal levels using the a.g.c. voltages lies in obtaining two receivers with sufficiently similar a.g.c. characteristics. Although both receivers in the diversity unit were of the same type, their a.g.c. characteristics were quite different. Therefore one of the a.g.c. voltages was passed through a variable gain amplifier and a level shifter, this enabled the two a.g.c. characteristics to be fitted together. Even so, there are still slight differences in the two a.g.c. characteristics as will be seen in Section 5.1.

4.2. Selection on video signal-to-noise ratio

Both the problems mentioned in the previous section can be overcome by controlling the switch on video signal-to-noise ratio as shown in Fig. 5.

The video signal from each receiver is passed to the noise comparator and since, as a result of effective a.g.c. in the receivers, the two output signals are well matched in level (1 V p-p) it is only necessary to compare the amounts of noise on each signal. This is done by looking at lines 6 and 319* (which contain no picture information) and amplifying the noise above 200 kHz. The filtering is necessary to remove any d.c. components from the line; it also excludes co-channel interference from television stations with standard frequency offsets.† The amplified noise is detected and, at the end of the line, the output is retained for one field period in a sample-and-hold circuit. This "sampled-and-held" waveform is smoothed to average the noise value over several fields. The noise voltages from both receivers are compared and the diversity switch made to select the receiver with the least noise.

When the input signal level is high, the video signal-to-noise ratio is not determined by the r.f. signal-to-noise ratio but by noise on the transmitted signal. Under such conditions the noise measuring circuits will measure the same value of noise on both channels. The result of this would be that the switch would dither unnecessarily. To avoid such a situation a small amount of backlash may be added. In the experimental diversity unit this was not necessary since small inherent differences in the noise measuring circuits biased the unit to one channel at high signal levels. A better solution, adopted for the service equipment, is to give a preferred choice when both signals are above a threshold value.

4.3. Video switch

The video change-over switch is controlled by the field synchronizing pulses, so that it can only act between the first and second equalizing pulses. This has the advantage over a non-synchronous switch that, if there are timing differences between the video signals, then the television receiver has 18 lines to recover from the switch point until picture information starts. Any brightness change through a small inequality of the two video signals will also be less evident when the switching occurs in the field-blanking period.

* subsequent equipment will use lines 12 and 325.

† the possibility of making the switch respond to such interference is being examined.

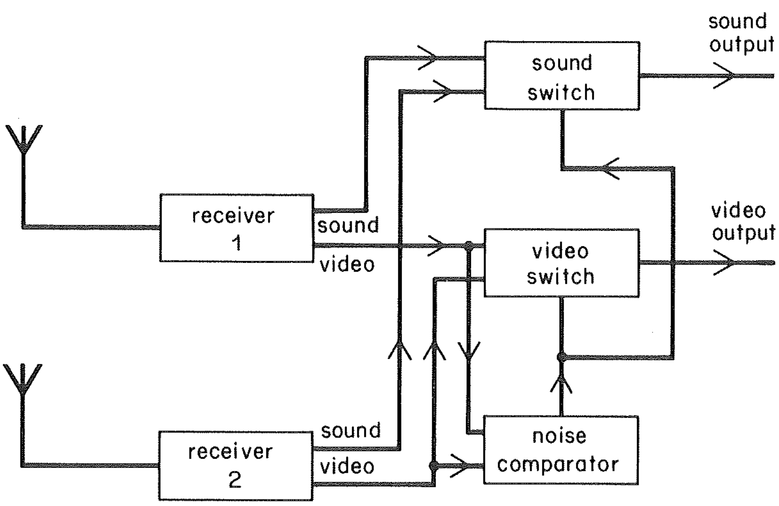

Fig. 5 - Selection on video signal-to-noise ratio

The switching is done by solid-state CMOS CD4066 switches, which are fast acting with a change-over time of less than 35 ns. Care was taken to ensure that the gain and d.c. levels of the two video signals were identical to reduce switching transients.

4.4. Sound switch

The sound switch operates at the same time as the video switch and also uses a CD4066 solid-state switch. As with the video switch, the gain and d.c. levels of the two receivers were set to be the same so that no transient spikes were caused by the switch.

5. Laboratory tests

5.1. Static tests

Fig. 6 shows the arrangement for static tests of the operation of the diversity switch.

Attenuator 1 was set to give a particular signal level at the input of receiver 1. Attenuator 2 was then adjusted until the diversity switch operated. Table 2 shows the difference in the settings of the two attenuators for various signal levels.

Under a.g.c. control, the signal levels at which the

TABLE 2

Operation of diversity switch under quasi-static conditions

(a) **AGC control**

Signal at Receiver 1 (dB rel. 1 μV)	Difference between Attenuators 1 and 2
60 dB	3 dB
50 dB	0 dB
40 dB	–2 dB
30 dB	–4 dB

(b) **Video signal-to-noise ratio control**

Signal at Receiver 1 (dB rel. 1 μV)	Video signal-to-noise ratio	Difference between Attenuators 1 and 2
70 dB	46 dB	6 dB
60 dB	44 dB	1 dB
50 dB	36 dB	0 dB
40 dB	27 dB	0 dB
30 dB	17 dB	1 dB

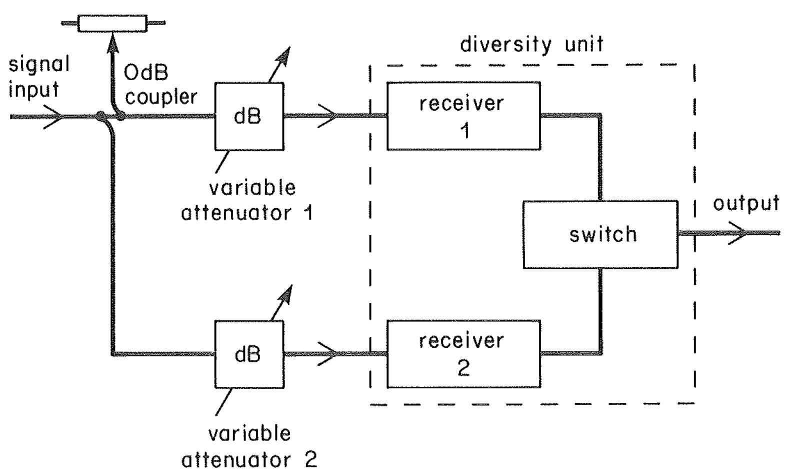

Fig. 6 - Arrangement for static tests

switch operates changes because of the difference in the two receiver a.g.c. characteristics.

Under noise control for lower signal levels the unit switches with the signal levels nearly equal (±1 dB). At higher signal levels (70 dB and above) any imbalance between the noise measuring circuits will predominate; this causes the 6 dB bias towards the right hand channel at 70 dB signal level.

5.2. Dynamic tests

Fig. 7 shows the arrangement for the dynamic tests.

The signal was split into two and one half fed to receiver 1 via a variable attenuator and a voltage-controlled attenuator which was driven by a low-frequency oscillator. In this way the signal to receiver 1 could be varied periodically in level to simulate a rapidly fading signal.

A dual-trace oscilloscope displayed both the control voltage for the attenuator and the switch control from the diversity receiver. The points at which the diversity switch operated could then be deduced, knowing the characteristics of the voltage-controlled attenuator and the settings of the two variable attenuators. Both systems of controlling the switch were tested for fast and slow rates of attenuation. The results obtained are shown in Table 3.

5.3. Visual effects of switching

The switch control was modified so that the video switch would "toggle" between receivers 1 and 2 at field frequency. This made any switching transients particularly noticeable on television receivers and monitors. Differences in the quality of the two signals fall roughly into three categories.

5.3.1. Amplitude inequality

When the switch is toggling rapidly, amplitude

TABLE 3

Operation of the diversity switch with rapidly-fading signals

(a) **AGC control**

Rate of attenuation	Signal level at 2 dB rel. 1 μV	Signal at 1 Change 2→1	Signal at 1 Change 1→2	Backlash
1 Hz	40 dB	43 dB	42 dB	1 dB
5 Hz	40 dB	45 dB	37 dB	8 dB

(b) **Video signal-to-noise ratio control**

Rate of attenuation	Signal level at 2 dB rel. 1 μV	Signal at 1 Change 2→1	Signal at 1 Change 1→2	Backlash
1/10 Hz	45 dB	46 dB	44 dB	2 dB
1/5 Hz	45 dB	47 dB	44 dB	3 dB
1 Hz	45 dB	49 dB	40·5 dB	8·5 dB
2 Hz	45 dB	52 dB	30 dB	22 dB

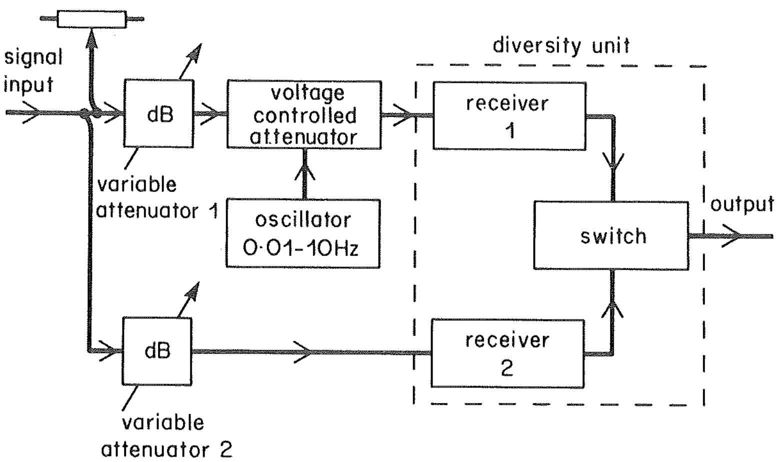

Fig. 7 - Arrangement for dynamic tests

inequality is apparent as a flickering on the picture and is especially noticeable in bright areas. If the switch occurs only occasionally then the change in contrast is not nearly so apparent as in the rapidly toggling case.

5.3.2. Time inequality

The signal to one of the receivers was delayed using lengths of coaxial cable, the longest delay that could be conveniently made in this way being about 1 μs. The diversity switch was made to toggle and the output video signal was viewed on a monitor and also, after re-modulation up to u.h.f., on a domestic receiver. As the delay between the two inputs was increased no effects were noticed until 70 ns of delay had been added. At this point the colour subcarrier phase-locked loop in the monitor began to lose lock, causing false colours at the top of the picture. The same effect occurred on the domestic receiver at a delay of about 90 ns. The delay was further increased, the picture on the domestic receiver recovered at about 125 ns and that on the monitor at about 150 ns.

The abrupt change in the phase of the colour subcarrier at switch-over can cause the subcarrier reference oscillator in the receiver/monitor to lose lock. This occurs when the phase step is about 110° in the monitor and 145° in the domestic receiver. The effect could be seen over the top third of the picture and was particularly noticeable on saturated colours.

Provided the delay between the two signals was a multiple of colour subcarrier period relatively large delays did not degrade the picture at switch-over. The greatest cable delay that was tried was 900 ns (4 cycles of subcarrier) and, apart from a very slight jitter at the top of the picture, no degradation was caused.

These effects were all observed with the diversity switch toggling at field frequency. When the switch was operated in single shot the effects were less noticeable.

5.3.3. Video frequency response inequality

During periods of severe multipath fading, frequency and pulse response distortion can be introduced into the transmission channel.

Both the amplitude and the phase of the video signal's frequency response can cause the switching to become visible. Differences in the amplitude response result mainly in a colour saturation change when the switch operates. This is particularly noticeable on single changes but not so noticeable when the switch is rapidly toggling.

Phase differences between the two video signals can cause two sorts of visual effects. Firstly, large differences in the phase response at colour subcarrier frequency can result in the subcarrier reference oscillator of the monitoring receiver losing lock on switching, giving rise to the same effect as was seen in timing inequality. Secondly, general phase differences are noticeable on switching because they cause changes in the position and quality of edges. This effect is particularly noticeable on a still picture with many sharp vertical edges such as test card.

In order to minimize this effect, it is proposed that the operational system should employ high-speed automatic equalizers following each receiver output and before the video selection switch.

6. Tests on Alderney

The diversity receiver was installed at Alderney in March 1976 and operated there until June 1976. The two aerials used were a 9·1 m diameter parabolic reflector aerial at 58·5 m above ordinance datum (a.o.d.) and a log-periodic aerial at 96 m a.o.d. For the first two months the unit operated on a.g.c. control and for the remainder of the period it operated on signal-to-noise control.

Two field strength recording receivers were used to make a chart record of the performance of the diversity unit. The recording receivers were coupled into the lines from each aerial and their outputs were fed into a slave switch which operated in synchronism with the diversity switch. The output of the slave switch was fed into one channel of a chart recorder while the other channel of the recorder was taken from the output of the field strength receiver connected to the parabolic reflector aerial. The recording from the parabolic reflector aerial acted as a control while the other recording shows the field strength selected by the diversity receiver. This arrangement is shown in Fig. 8.

The chart records show that the unit successfully removed fades by switching between the two aerials. Short sections of the chart recording are shown in Fig. 9 in which fading can be seen to be occurring. The darker trace represents the signal from the parabolic reflector aerial. The two traces on the chart recorder have been displaced vertically by about 10 mm and horizontally by about 2 mm in order to reduce over-writing.

Fig. 9(a) is a short section of the chart record showing the diversity switch operating under signal-to-noise ratio control. The record from the parabolic reflector aerial shows four periods of deep fading; these were all successfully removed by the diversity switch. It is interesting to note that the fade shown on the extreme left of the record occurred on both aerials but that the depth of the fade on the log-periodic aerial was much less than that on the parabolic reflector aerial.

Fig. 9(b) shows another short section of the chart record. This time the switch is operating on signal level, and the threshold level is superimposed on the record by the dotted line. When the transmitter first came on the air the diversity switch selected the log-periodic aerial. The signal from this aerial fell until it reached the threshold level at (1); the switch then operated and the parabolic reflector aerial was selected. A fade occurred on the parabolic reflector aerial and the diversity switch operated

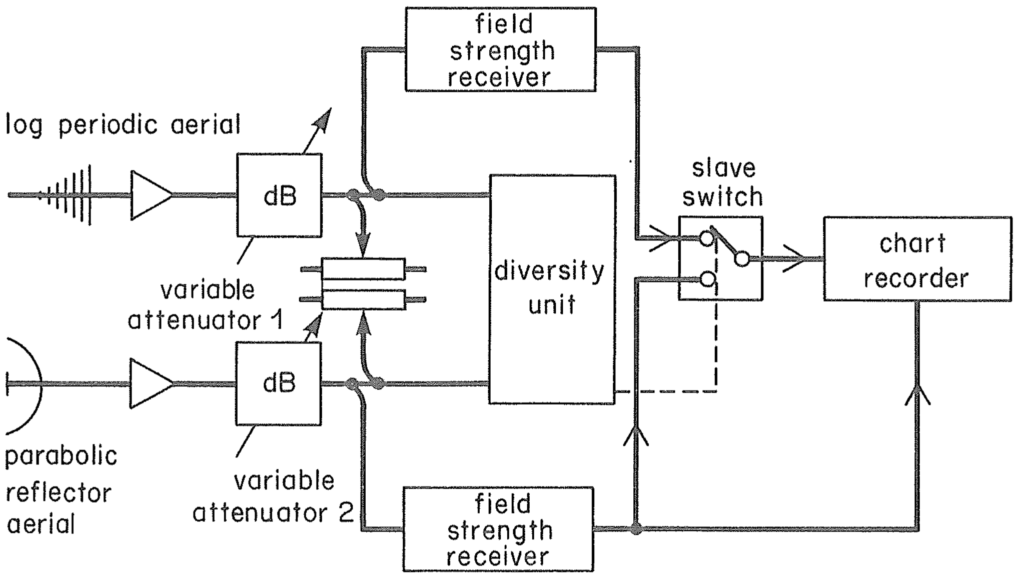

Fig. 8 - Experimental installation on Alderney

at point (2) to re-select the log-periodic aerial. The switch remained on the log-periodic aerial for the remainder of the period.

7. Performance expected of the service installation

The design of the service unit by the BBC Designs Department has been guided by, and uses some features of, the experimental switch. At the time of writing, the first model is in service although the design is not yet finalized. This assessment of the final performance is therefore somewhat speculative.

7.1. Use of backlash

Maximum diversity gain will be obtained when the backlash is minimal. However, it may be difficult to eliminate entirely the minor visual effects of switching. It may then be desirable to introduce a small amount of backlash to reduce the number of switching operations taking place. A suitable value of backlash might be 1 dB. Whether this will prove to be the best compromise between diversity gain and the frequency of switching can only be determined after a period of sustained operation covering both winter and summer conditions.

The introduction of backlash gives the same effect

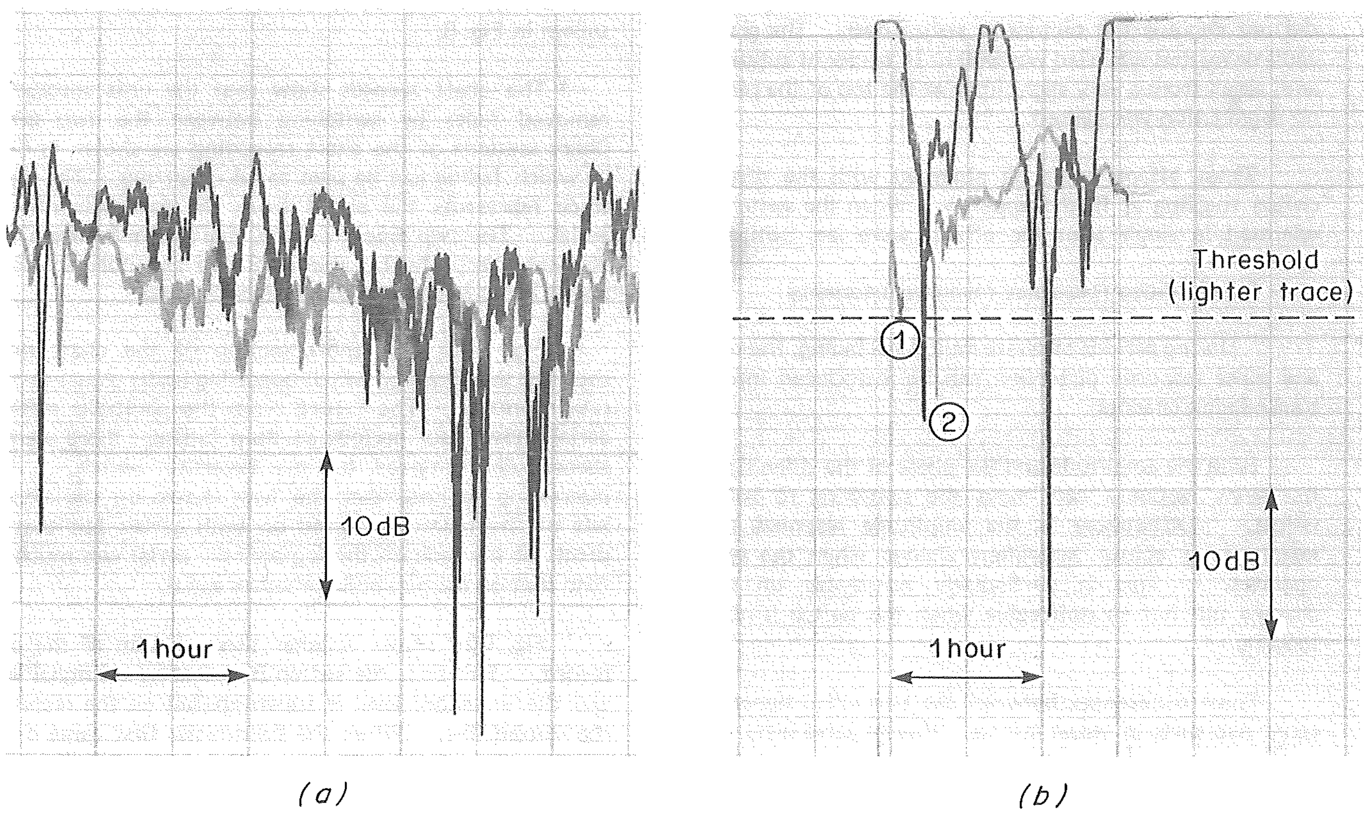

Fig. 9 - Examples of chart recording with experimental installation on Alderney

in practice as the use of unequal signals (see Section 2.4.). Thus, with 2 dB of backlash introduced to otherwise equal signals, the diversity gain will be relative to a notional signal 1 dB less. In other words, the diversity gain will be reduced by half the value of backlash.

7.2. Signal-to-noise ratios

The signal-to-noise ratios expected on the feeds from the two aerials in use at Alderney are shown in Table 4. The idealized diversity gain is given by Fig. 2; this will be reduced by backlash and also by any substantial correlation between the signals from the two aerials. Whilst measurements of correlation are rather few, the indications are that the coefficient of correlation is small. The practical diversity gain should therefore be close to that given in Table 5. Table 6 gives the corresponding signal-to-noise ratios to be expected with dual diversity.

In principle, it would be possible to use signals from other aerials on the site in three- or four-channel diversity, but the advantage would be small and not likely to justify the additional complication.

8. Conclusions

A two-channel experimental diversity system has been built and tested both in the laboratory and on the island of Alderney. The laboratory tests highlighted some of the

TABLE 4

Signal-to-noise ratio expected with individual aerials

Channel 26 — BBC-2

Aerial	Signal-to-noise ratio exceeded for proportion of time 50%	95%	99%	99·9%
Log-periodic array	50 dB	45 dB	39 dB	30 dB
parabolic reflector	46 dB	41 dB	35 dB	26 dB

Channel 33 — BBC-1

	Signal-to-noise ratio exceeded for proportion of time 50%	95%	99%	99·9%
Log-periodic array	47 dB	42 dB	36 dB	27 dB
parabolic reflector	44 dB	39 dB	33 dB	24 dB

TABLE 5

Practical diversity gain

	Signal-to-noise ratio exceeded for proportion of time 50%	95%	99%	99·9%
Intrinsic gain	4 dB	7 dB	8 dB	9 dB
Practical gain allowing for backlash and correlation	2 dB	5 dB	6 dB	7 dB

TABLE 6

Signal-to-noise ratios with dual diversity

	Signal-to-noise ratio exceeded for proportion of time 50%	95%	99%	99·9%
Channel 26 (BBC-2)	50 dB	48 dB	43 dB	35 dB
Channel 33 (BBC-1)	47 dB	45 dB	40 dB	32 dB

conditions that must be met to keep the visual effects of switching to a minimum. The rebroadcast link receivers must be well matched to give identical video signals and the video signals should be matched in time-delay at the change-over switch to better than 50 ns.

The tests on Alderney showed that fades could be effectively removed using the diversity unit and two spaced aerial systems. A system based on the experimental unit is now in operation on Alderney providing the television feed to the Channel Islands.

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